Tornado Warning Verification for the Lincoln, IL, Indianapolis, IN, and Wilmington, OH National Weather Service Offices

An Honors Thesis (HONR 499)

By

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Ball State University
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May 2016

Expected Date of Graduation

May 7, 2016

Abstract:

Severe weather is a recurring threat to life and property across much of the United States every year. The most destructive of these weather types, and usually the most feared, is the tornado. When tornado warnings are issued people are told take shelter, or at least that is the goal. However, with the vast majority of tornado warnings issued not actually correlating with a tornado occurring, some are starting to ignore these vital safety messages. Additionally, multiple tornadoes every year go without warnings, or warnings that came too late.

This study looks at ten years of data, from 2004 to 2013, for the National Weather Service Weather Forecast Offices in Lincoln, Illinois, Indianapolis, Indiana, and Wilmington, Ohio. The goal of this study is to provide an analysis of how each of these offices does in terms of issuing tornado warnings that verify with a tornado, as well as how many tornadoes occurred without a tornado warning. A geospatial and temporal analysis was done using data for tornado paths and tornado warnings for the above National Weather Service offices. This analysis revealed that on average roughly 20% of tornado warnings issued will verify and that more than 30% of tornadoes will not receive any kind of warning, though these tornadoes are almost always on the weak end of the EF scale. Using this data, a conclusion is drawn that the most effective means of helping the public is a better effort in communication and outreach about tornadoes and tornado warnings by the National Weather Service.

Acknowledgements:

I would like to thank Dr. David Call for advising me on this project. Dr. Call has been a source of guidance and advice through my entire college career and his help on this project was much appreciated.

I would also like to thank Dr. Reuben Allen who helped me get the idea for this thesis project started in his cartography class. His help made the whole research topic possible.

Introduction:

Living in the United States, especially in the Midwest, severe weather season is just an inevitable part of life. While one is far more likely to suffer property damage or injury from a flood, lightning, wind, or hail, tornadoes are typically feared the most. In just the ten years from 2004 to 2013 data obtained showed that the Lincoln, IL, Indianapolis, IN, and Wilmington, OH, Weather Forecast Offices (WFOs) experienced 482 total combined tornadoes in their county warning areas (CWAs; see Figure 1). During this same time these offices issued a combined total of 1,289 tornado warnings, with 270 of these warnings actually issued for a storm that produced a tornado. This results in a combined accuracy of only 20.95%. While issuing vastly more warnings than the number of actual tornadoes is a concern, perhaps more concerning is the fact that during this time period 160 tornadoes went without a tornado warning, either because a warning did not cover the area the tornado occurred in, or a warning came too late. That means 33.2% of tornadoes in this region came without a warning. With this information in mind, we come to the reasoning behind this study. The goal is to analyze how each WFO did with regard to warning verification and missed tornadoes in their CWAs and to make conclusions based on the geographical distribution of this data as to why the data looks the way it does and what this means in the bigger picture of informing the public about severe weather risks.

Methodology and Process:

The data for this study comes from the National Weather Service (NWS) Storm Prediction Center (SPC), which provided the tornado paths data, and the Iowa Environmental Mesonet (IEM) ran by Iowa State University of Science and Technology, which provided the tornado warning data. The methodology for analyzing this data for this study was somewhat simple, but was not without its nuances. In the most basic terms a tornado warning is verified if a tornado path at any point intersects or is wholly contained within a tornado warning polygon during a time at which both could conceivably be occurring. This is where some subjectivity comes in. The database of tornado paths obtained from the SPC tracks many values for each tornado, but the only useful ones for verification are location, an estimated start time, and a path length. No ending time is provided. For that reason we must defer to previous published NWS data to obtain an average forward speed for each tornado. This is stated by the NWS to be 30 mph. As of such the path length, which is given in miles, can be used to calculate an estimated end time for each tornado, though this is accepting that fact that all tornadoes have a different speed and will likely introduce some amount of error in both terms of verified and unverified tornado warnings. With this in mind, a tornado warning did not verify if the tornado in question was always outside the tornado warning polygon or if the tornado path intersected or was wholly within a polygon prior to the warnings issuance and the warning was not issued before the tornadoes estimated end time. As for warned and unwarned tornadoes the methodology was straight forward. If at any point during the estimated lifespan of the tornado did its path intersect or become wholly contained by a warning polygon active during this same time period the tornado is marked to have been warned for. Everything else is marked as unwarned. For the purposes of this study we did not include special categories for warnings that came at or after the time the tornado began, as lead time was not the focus of this research.

Moving on to the process for this research, most of the time was spent using ArcMap, a geospatial analysis program, to verify warnings and the warning status of each tornado. The process began by downloading the tornado path shapefiles from the SPC SVRGIS database and the warning polygons from the IEM Archived NWS Watch/Warnings database. The tornado paths shapefile contained all tornadoes from 1950 to 2015, and was reduced to the time period of interest by using a "select by attributes" selection to separate out the time period from 2004 to 2013 into a separate shapefile for further use. These tornado paths were further reduced to just the area of interest by downloading a shape file for all county warning areas from the NWS and then using another "select by attributes" selection to separate out our desired CWAs into a new shapefile. At this point, and for the reason of not wanting to miss any tornado paths that fell within the CWAs, a buffer was created of 0.5 decimal degrees around the selected CWAs and used to clip the tornado paths that intersected the buffer from the full group. A "select by location" selection was performed to select the subset of this grouping of tornadoes for each CWA, resulting in the creation of three final shapefiles containing tornado paths, one for each CWA. (Any tornado path that was later found to be wholly outside the CWA and never intersected a tornado warning from that CWA was deleted from the study database.) The warning polygons were downloaded for specifically the years and CWAs desired and no sorting needed to be done at this stage.

Following this sorting, new fields were added to each of the tornado path shapefile's attribute tables and the warning polygon shapefile's attribute tables. These fields were "warned": a yes or no field for the tornado path table, and "verified": a yes or no field for the warning polygon table. To make comparisons easier, and since the tornado path shapefiles kept date and time in separate categories, the "concatenate date and time fields" tool was used, followed by a tool to convert the time from a 24 hour clock to the traditional AM/PM system familiar to most. The time portion of this data was already set to Central Standard Time (CST) for all dates in the table. The warning polygons also had their time information converted to a time field in ArcMap, but further needed to have a "convert time zone" tool ran on them in order to move from the Universal Time Coordinate (UTC), which is how the data was recorded, to CST for comparison with the tornado path data. At this point both sets of data were sorted by date and each tornado path was selected, one by one, zoomed to, and verified by selecting warnings that occurred around that time period to see if any covered the selected tornado in both space and time. If such an event occurred the tornado was marked as having been warned and any warnings that it intersected during its lifespan were marked as being confirmed. Since the database of NWS warning polygons, the actual subset area for which a tornado warning is issued (can included small portions of or entire counties), also includes a polygon representing each county covered by the NWS warning polygon, only the actual NWS warning polygons were used for verification, though if the warning did verify, each county polygon covered by the NWS warning polygon was also marked as having been verified. This process continued for all 482 tornadoes in the study.

Following the completion of the verification process, the warning data was aggregated to the county level by first using a "select by attributes" selection to separate out the county polygons (which are in the actual shapes of the counties that had warnings issued over them) from the NWS warning polygons, placing them into a new shapefile. A new field was then added called verification values. This was a binary system consisting of a value of 1 for a verified warning and 0 for an unverified warning. This new file was then dissolved based on a field labeled NWS_UGC, which was a unique code used for each county. In this dissolve, statistics were calculated in the form of a count for the verification field, this counted every yes or no as a value of 1 and resulted in the number of warnings issued in that county being output to the dissolved feature's attribute table, and a sum for the verification value field, which resulted in the number of warnings issued in the county which actually verified being added to the dissolved feature's attribute table. From these two output values another field was added and able to be determined. A verification percentage field was added and simply consisted of the value from the verification number field being divided by the value from the number of warnings field and multiplied by 100.

Before the creation of the final results several more areas of data needed to be analyzed and recorded. The majority of which was the number of tornadoes and unwarned tornadoes for each county. For this process a county was selected and a "select by location" selection was performed within the selected county on the tornado paths layer to select all of the tornadoes that intersected or were contained by the county polygon. This number was recorded and then a "select by attributes" selection was done on the selected tornadoes from the previous selection to determine how many of them were unwarned. This process was repeated for every county within the study area. Additionally the NWS warning polygons were separated from the county polygons to another shapefile, in a process matching the way the county shape polygons were separated above, in order to gain information for the entire CWA about what percentage of tornado warnings verified versus those that did not. This value is different than the number represented in the final output maps created on a county by county basis. Following this step the maps, tables, and graphs in the attached "Tables and Figures" section were able to be created and conclusions based on these were able to be made.

Challenges and Potential Causes of Error:

The largest challenge faced while undertaking this study was the extreme amount of verification work that must be done by hand. While ArcMap is great for automating work tasks that are purely about spatial relations, it does not do a good job when adding in a time component to the selection. Additionally, creating any way of automating this process, outside of an advanced python script, would prove difficult especially due to the subjective nature of some of the verifications with regard to estimated end times based on an average speed related to the path length of the tornado. This is where we come to our first place of potential error, estimated end times for each tornado. Since this value is calculated only on the average speed of a tornado given by the NWS at 30 mph, the process is almost certainly introducing error as tornadoes have been known to go from near stationary to over 100 mph in terms of forward momentum, depending on the storm. Additional error comes from the fact that the tornado paths stored by the SPC database only are in the form of start and end points. Any point in-between where the path may have curved or circled is not included. This means warnings that were close to the tornado path that did not verify may have done so if higher resolution data was available. Finally, it is entirely possible that some error may have occurred as a result of the human factor in this study. The vast majority of this data was verified by hand, which resulted in hours upon hours of working with spreadsheets. It is easy to see how a row may have been missed or something overlooked through this process, though every effort was taken to avoid such error.

Individual Results by CWA:

Wilmington, OH CWA

Overall the Wilmington CWA performed the best when it came to verification of tornado warnings, at 24.76% (Table 1), though it placed second on the list for number of unwarned tornadoes, with 50 tornadoes that occurred without a tornado warning. Looking at Figures 2 and 3 there is no strong geographical bias as to where tornadoes are likely to form or where a tornado is likely to go without a warning. In fact there is only a loosely visible correlation between where the most tornadoes occur and where the most warnings are issued when comparing Figure 2 and Figure 4. However, when looking at Figures 4, 5, and 6, we can see a bias toward more warnings being issued in the eastern and central regions of the state. Additionally these warnings are also more likely to verify based on the verification percentage and the standard deviation of warning verification. A possible reason for this higher verification is that in general radar coverage is less dense in this region (Figure 7). This would mean any rotation signatures that appear on the radar here are likely to be indicative of strong rotation, meaning a likely rotating storm that is capable of producing a tornado. As of such, the likelihood a warning issued on that storm will verify is increased. Furthermore, when comparing the verifications to Figure 1, I do not believe that size or duration of the tornadoes in the Wilmington CWA had any real bearing on the verification biases seen in Figures 5 and 6.

Indianapolis, IN CWA

The Indianapolis CWA had the worst overall accuracy in our study, only scoring 18.26%, but also had the lowest number of unwarned tornadoes at 38 (Table 2). In the Indianapolis CWA we see a loose correlation between where a tornado is likely to form and where a tornado warning is likely to be issued (Figures 8 and 9). Neither of these results show any strong geographical biases. When observing the locations in which a tornado is likely to go unwarned, a small bias is shown toward the southern and central portions of the state (Figure 10), but this can only be seen to correlate with Figures 8 and 9 in a loose way, and not in any way that appears to be statistically significant. When moving toward the percentage of verified warnings (Figure 11) and the warning verification standard deviation (Figure 12) a relatively strong bias appears toward the northern part of the CWA. Radar coverage is not likely to have been a factor in this bias, as the entire state is shown in Figure 7 to have relatively uniform radar coverage. However, when looking at Figure 1, we see several long tracked and large tornadoes that moved over the northern portion of the CWA. These tornadoes are easier to see than smaller ones on radar and are therefore easier to verify multiple warnings off of. These factors likely resulted in the verification bias we see toward the northern counties for the Indianapolis CWA from 2004 to 2013.

Lincoln, IL CWA

The Lincoln CWA scored in the middle for accuracy in our study, with an overall value of 21.04% of warnings verifying, but did the worst in terms of unwarned tornadoes with 72 tornadoes going without a warning (Table 3). Additionally, Lincoln issued the most tornado warnings out of the three areas studied, issuing 499 warnings over the ten year period. For the distribution of data in the Lincoln CWA we see a small geographical bias in the tornado occurrence (Figure 13) and the tornado warning issuance (Figure 14) toward the central portion of the CWA extending from both the eastern and western sides. In this case the areas that receive the most tornadoes do appear to be correlated to the areas that see the most tornado warnings. Oddly enough, the areas that see the most unwarned tornadoes also show geographic bias toward the central portion of the CWA (Figure 15) and appear to be matching in correlation to the areas that see the most tornadoes (Figure 13). I do not believe these correlations to be caused by any factor outside of the sheer number of tornadoes that occur in this region. Radar coverage is mostly consistent across the CWA, with some minor exceptions, and there does not appear to be any other factors at play here. Simply put, a large number of tornadoes will likely result in a large number of warnings, but is also likely to result in more chances to miss a tornado, resulting in a higher value for the number of unwarned tornadoes in this region.

Moving on to the verification percentages (Figure 16) and the verification standard deviation (Figure 17) we continue to see bias toward the central portion of the state, although the bias shifts a little to the north from the biases mentioned above and seen in Figures 13, 14, and

15. I feel this bias does come as the result of more factors than just the number of tornadoes that occurred. As we move toward the northern portion of the CWA we see the radar network become somewhat denser when compared to the southern portion. As of such, rotation in the storms further north is more easily detected. This likely results in a better understanding of the storm before a warning is issued and results in warnings that are more likely to verify as having a tornado. Additionally, looking at Figure 1, it is clear that large and long lived tornadoes have affected most portions of this CWA and I do not believe they had much of an impact on the bias of the verification scores in this case.

Conclusions Based on Final Results:

In the article *Science and Psychology: Why People Ignore Tornado Warnings* written for AccuWeather by Molly Cochran she quotes Expert Senior Meteorologist Henry Margusity as saying that "People have become desensitized because too many false alarms are issued" with regard to the number of tornado warnings. She mentions how the current system of warning polygons is better than the old way of issuing warnings for the entire county, but it is still not accurate enough. Our findings from this study would appear to further back up those claims. Over our study area the Lincoln CWA scored a 21.04% warning verification, the Indianapolis CWA an 18.26% verification, and the Wilmington CWA a 24.76% verification (Tables 1, 2, and 3). This data is alarming to say the least. Even the best performing NWS office in our study area is only verifying less than one fourth of all the warnings that they issue. In fact the highest county based verification across the entire study was 60%. This occurred in the Wilmington CWA for Fairfield County, Ohio. It was the only place a verification value exceeded the 50% mark. While meteorologists understand that weather prediction is a challenging and inexact science, the public does not. In a world where you wake up and get the weather on your phone every morning presented in a way that is meant to relay accuracy, it is easy to see why the average person may feel they don't need to listen to a warning because three fourths of the time they will not result in a tornado. In an article titled *Report: Many Joplin residents ignored first tornado warnings* posted to USA Today, a National Oceanic and Atmospheric Administration report is quoted as saying "The majority of surveyed Joplin residents did not immediately go to shelter upon hearing the initial warning." In the interest of public safety, verification numbers need to get better, though the solution is not simple.

When looking for a solution some simply argue that the NWS needs to be more discerning and take more time before issuing a warning. While this is good in theory, our study also revealed that 160 tornadoes, or 33.2%, of tornadoes, occurred without a warning. A number of these occurred with a warning that came out too late in order warn anyone of the tornado threat. The simple fact is that our radar network is not adequate enough to detect every tornado. In Figure 7 we see a representational map from NOAA of radar coverage within the US. While coverage between 4,000 and 6,000 feet is seen as ok in this chart, it is difficult to use this data to detect a tornado, as most tornadoes are small and form in the lowest regions of the storm. Compounding this problem is the time interval between radar scans. According to the National Severe Storms Laboratory (NSSL) the average tornado is on the ground for about 5 minutes. Even with the new SAILS protocols used by the NWS radar network, the lowest scans, which could reveal a tornado, are only updated every 2.5 minutes. This means someone observing radar data may only have 1 or 2 scans to detect rotation. This is the main reason most unwarned tornadoes are on the weaker end, either an EF-0 or EF-1 (Figures 18, 19, and 20), while it is very unlikely for a larger or longer lived tornado to go without a warning.

With this information in mind, the most likely way to improve reactions to tornado warnings is through enhanced community outreach and public education. The goal of this effort would be for the public to better understand the nuances of tornado warnings and severe storms, as well as preparing the public to take warnings in a more serious fashion. With the current technology it does not appear that we can increase the accuracy of tornado warnings beyond the current threshold, without running the risk of increasing the number of tornadoes that go without a tornado warning. (A representation of the unwarned tornadoes compared to the total number of tornadoes for each CWA can be seen in Figures 21, 22, and 23.) It is likely these numbers will improve in future generations as radar technology improves and radar coverage gets better, but for now the best options is to do all that we can in order to inform the public, giving them the tools they need to understand how and when to take shelter from a tornadic thunderstorm.

Tables and Figures

Table 1: This table shows the total number of tornadoes, number of unwarned tornadoes, the number of tornado warnings, the number of verified tornado warnings, and the percent of warnings verified for the Wilmington, OH WFO.

Year	Tornadoes	Unwarned Tornadoes	Tornado Warnings	Verified Warnings	Percent Verified
2004	9	4	21	5	23.81%
2005	3	1	16	2	12.5%
2006	22	13	26	9	34.62%
2007	4	1	19	3	15.79%
2008	10	4	35	5	14.29%
2009	12	3	48	8	16.67%
2010	18	2	42	13	30.95%
2011	33	13	62	19	30.65%
2012	19	5	32	12	37.5%
2013	7	4	18	3	16.67%
Totals:	137	50	319	79	24.76%

Table 2: This table shows the total number of tornadoes, number of unwarned tornadoes, the number of tornado warnings, the number of verified tornado warnings, and the percent of warnings verified for the Indianapolis, IN WFO.

Year	Tornadoes	Unwarned Tornadoes	Tornado Warnings	Verified Warnings	Percent Verified
2004	28	8	73	18	24.66%
2005	10	2	60	8	13.33%
2006	16	5	64	11	17.19%
2007	6	3	14	3	21.43%
2008	15	5	29	10	34.48%
2009	5	2	26	2	7.69%
2010	8	2	59	7	11.86%
2011	19	4	87	13	14.94%
2012	4	2	24	3	12.50%
2013	20	5	35	11	31.43%
Totals:	131	38	471	86	18.26%

Table 3: This table shows the total number of tornadoes, number of unwarned tornadoes, the number of tornado warnings, the number of verified tornado warnings, and the percent of warnings verified for the Lincoln, IL WFO.

Year	Tornadoes	Unwarned Tornadoes	Tornado Warnings	Verified Warnings	Percent Verified
2004	31	14	97	14	14.43%
2005	6	3	21	3	14.29%
2006	74	23	91	26	28.57%
2007	6	4	28	2	7.14%
2008	12	3	70	8	11.43%
2009	18	6	44	12	27.27%
2010	16	4	39	10	25.64%
2011	22	8	58	14	24.14%
2012	14	3	24	7	29.17%
2013	15	4	27	9	33.33%
Totals:	214	72	499	105	21.04%

Figure 1: This map depicts all of the tornadoes that occurred from 2004 to 2013 across the indicated WFOs. The paths are shown and the magnitude of each tornado is also represented.

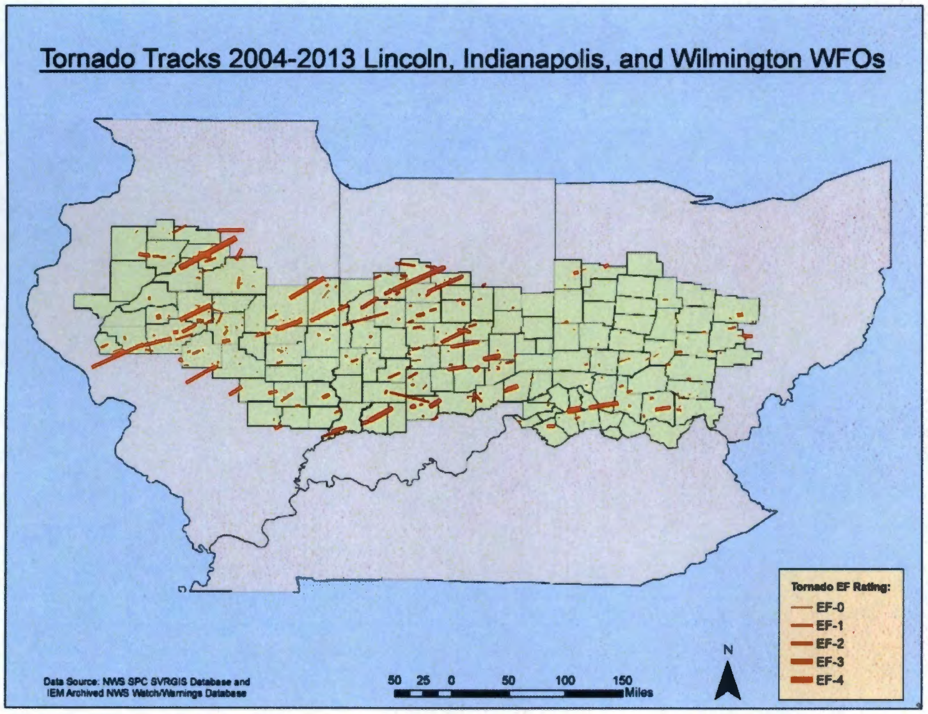


Figure 2: This map shows a county by county representation of tornadoes in this region.

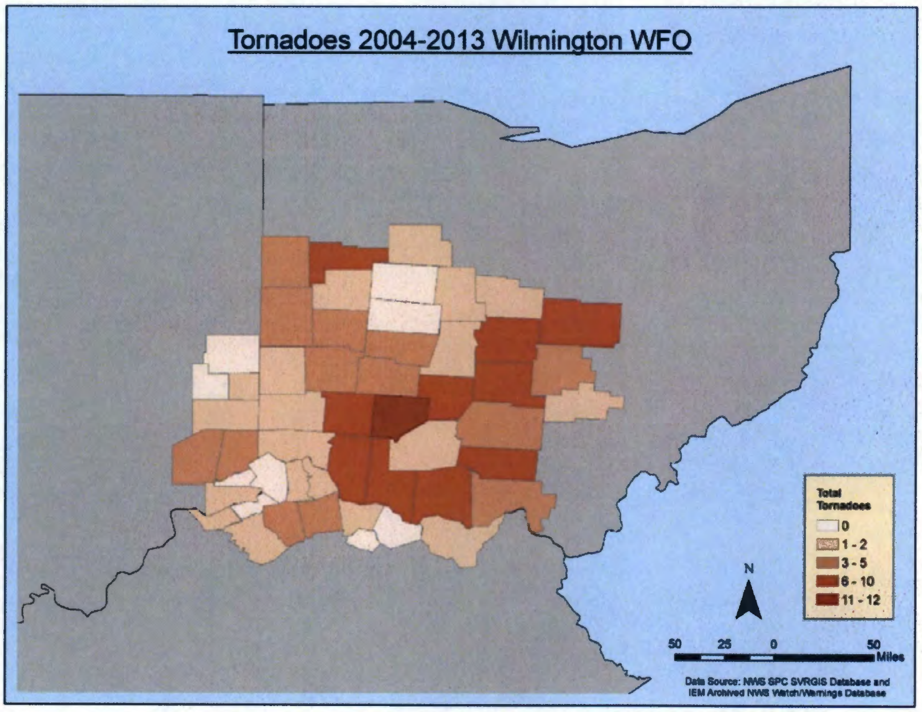


Figure 3: This map shows a county by county representation of unwarned tornadoes in this region.

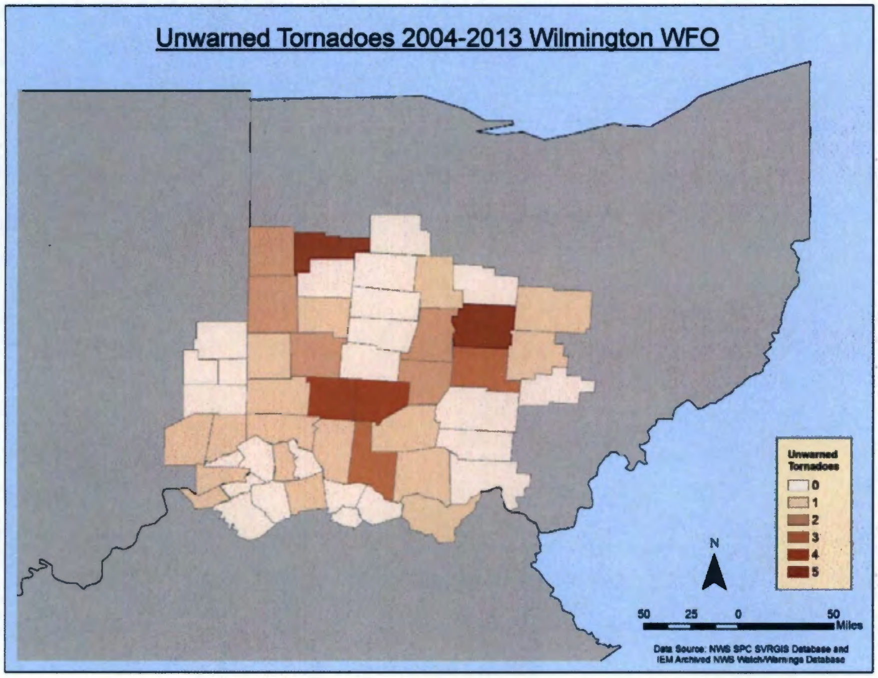


Figure 4: This map shows a county by county representation of tornado warnings in this region.

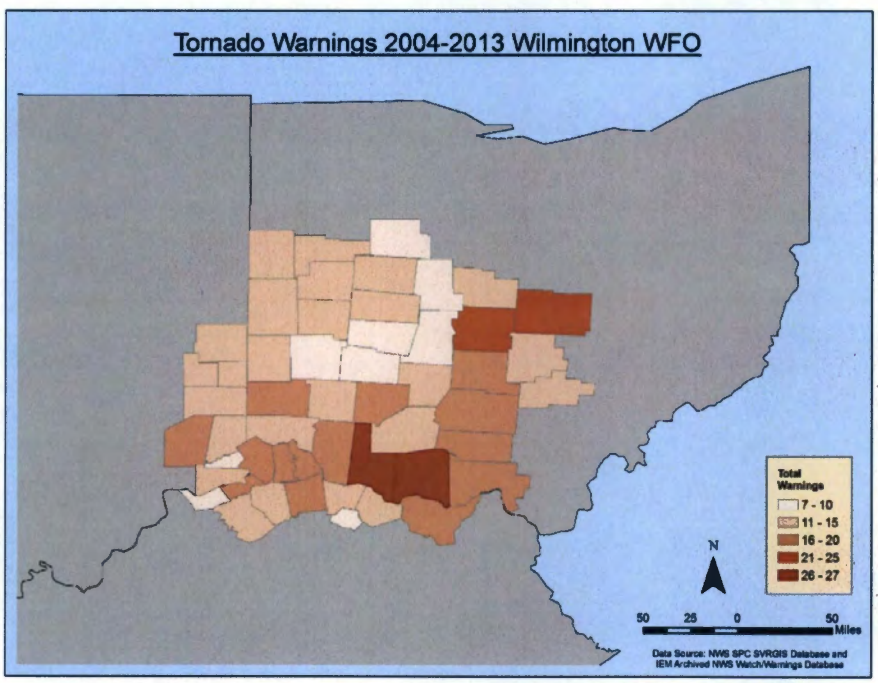


Figure 5: This map shows a county by county representation of tornado warning verification percentages in this region.

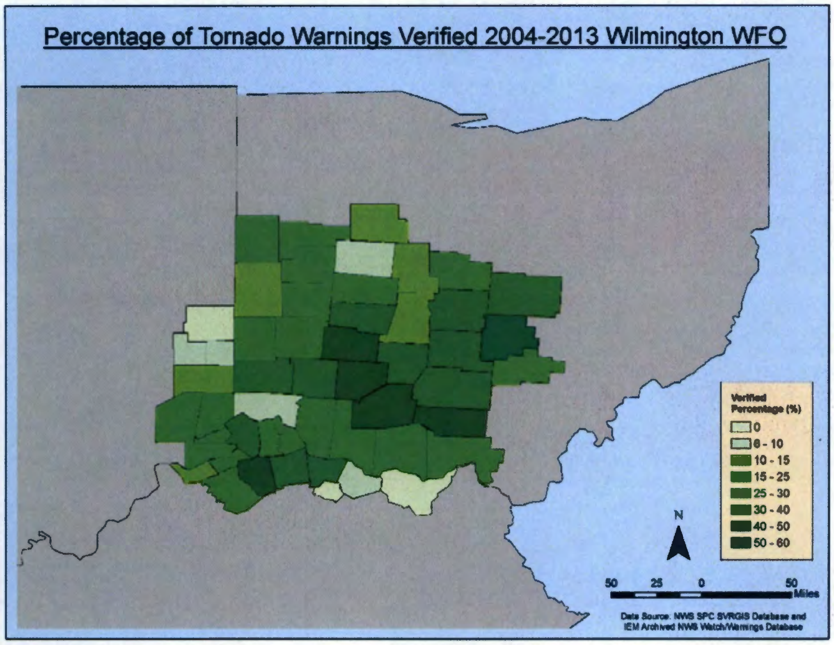


Figure 6: This map shows a county by county representation of the standard deviation of tornado warning verifications in this region.

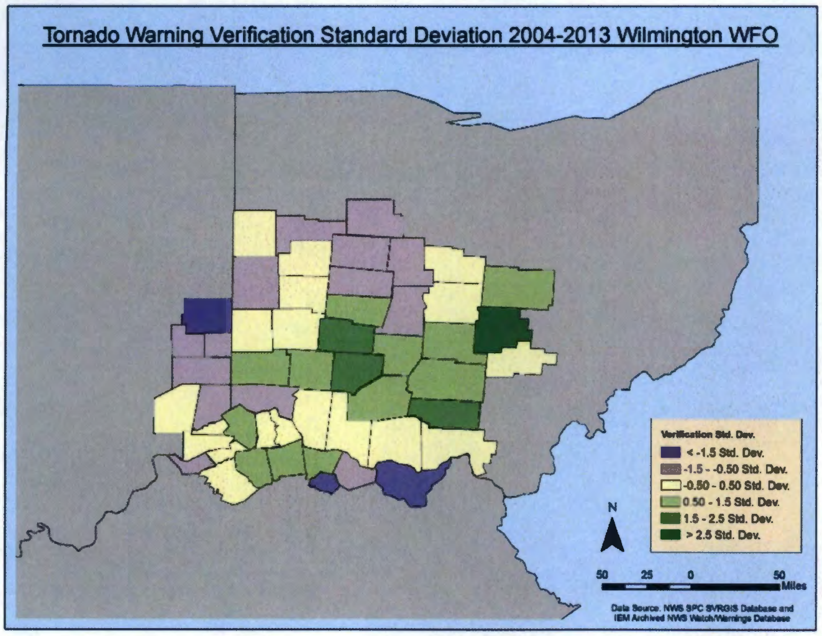


Figure 7: This map shows a representation of U.S. WSR-88D radar network coverage, depicted in terms of the radar beam height above the ground level.

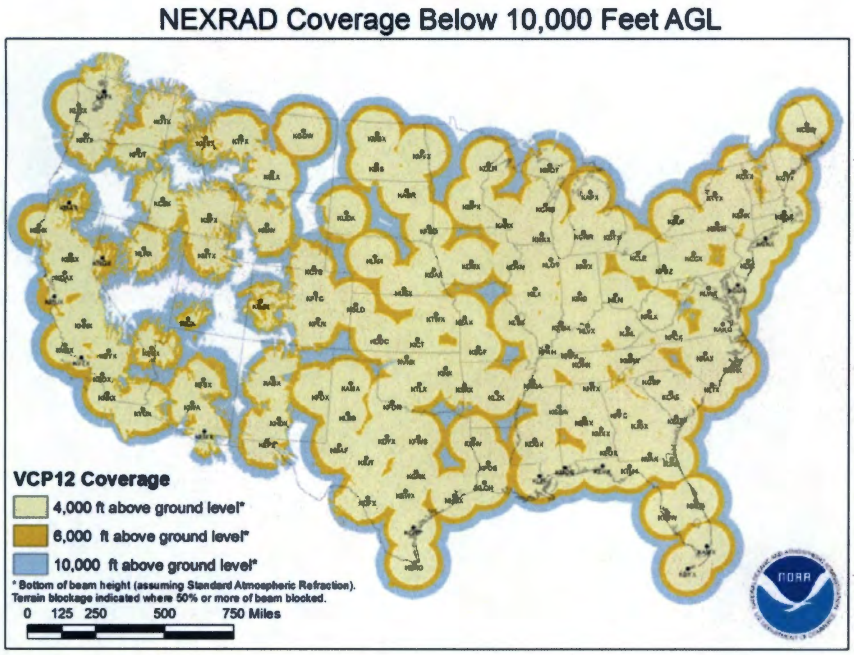


Figure 8: This map shows a county by county representation of tornadoes in this region.

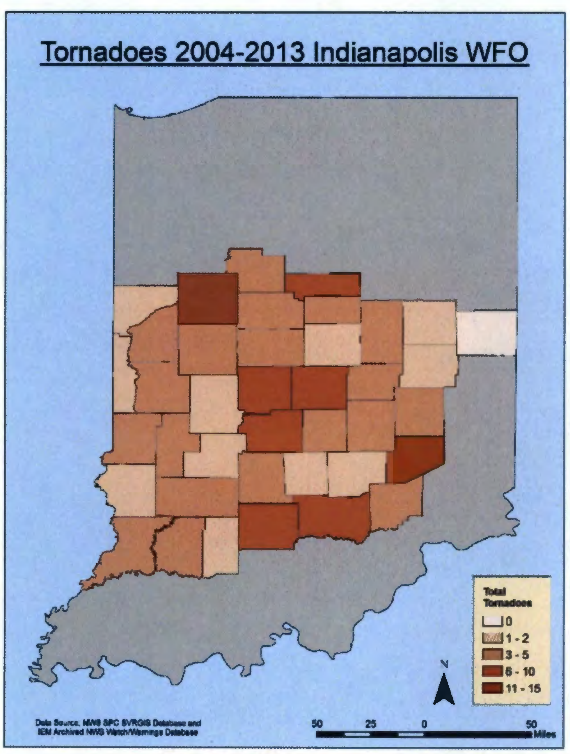


Figure 9: This map shows a county by county representation of unwarned tornadoes in this region.

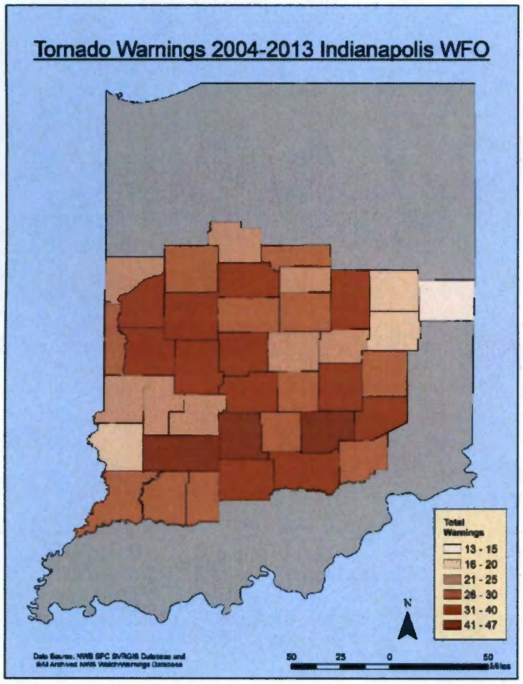


Figure 10: This map shows a county by county representation of tornado warnings in this region.

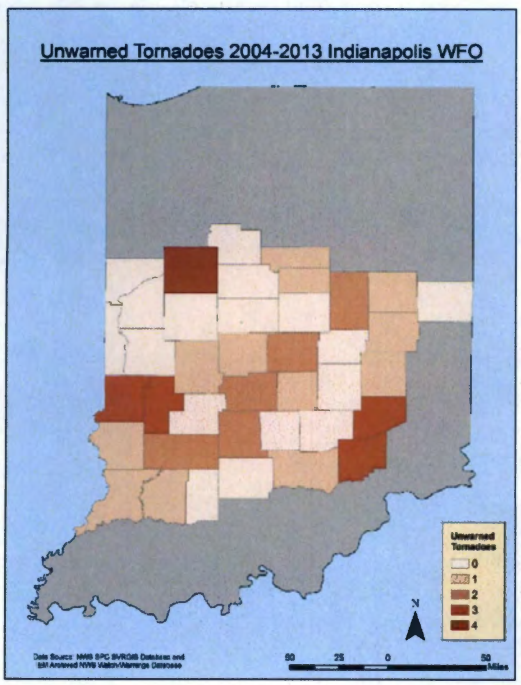


Figure 11: This map shows a county by county representation of tornado warning verification percentages in this region.

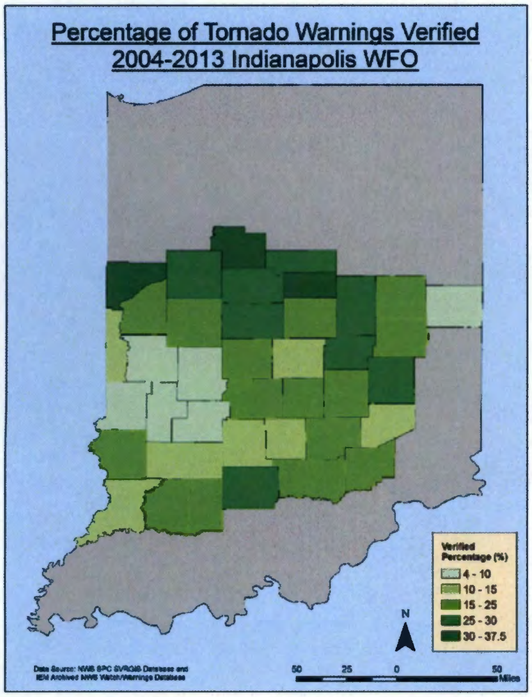


Figure 12: This map shows a county by county representation of the standard deviation of tornado warning verifications in this region.

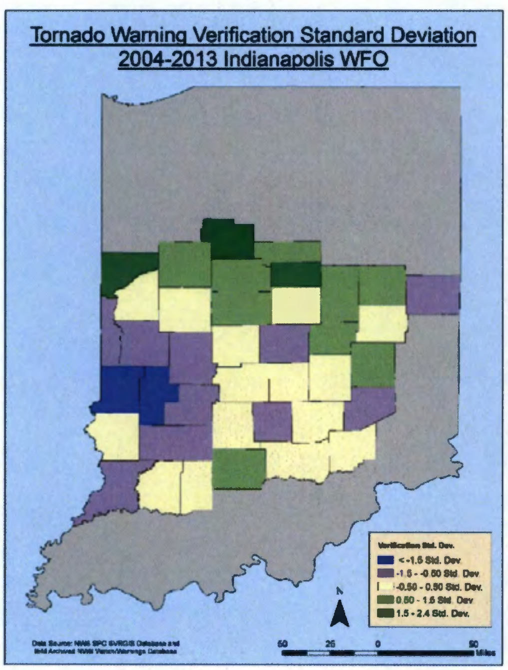


Figure 13: This map shows a county by county representation of tornadoes in this region.

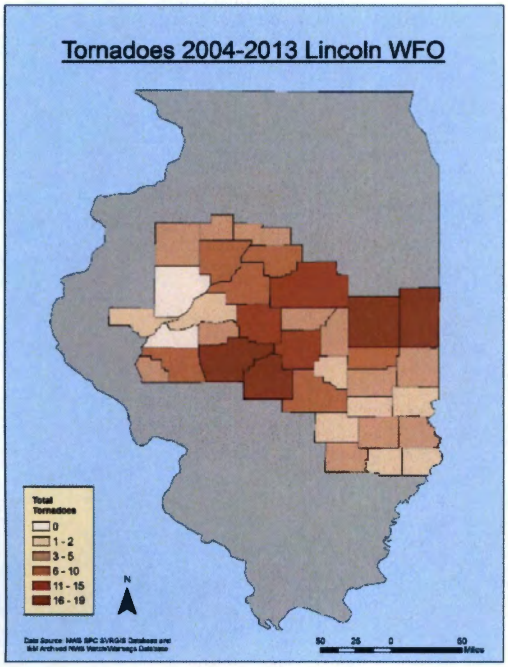


Figure 14: This map shows a county by county representation of unwarned tornadoes in this region.

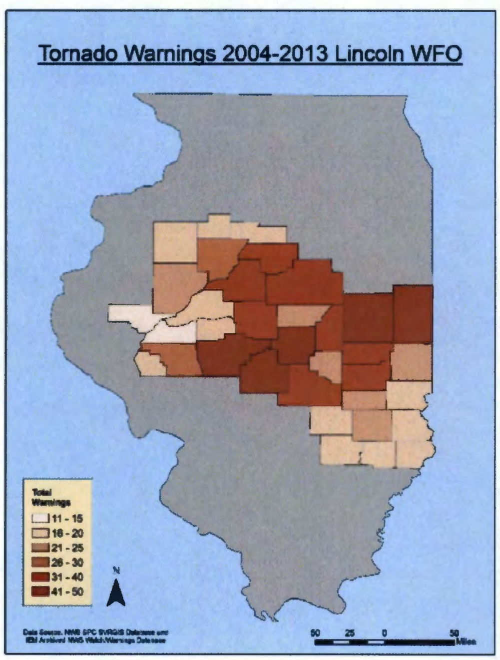


Figure 15: This map shows a county by county representation of tornado warnings in this region.

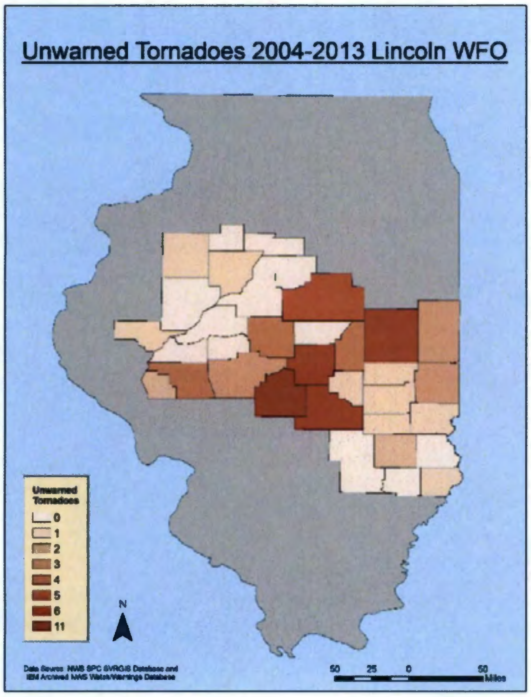


Figure 16: This map shows a county by county representation of tornado warning verification percentages in this region.

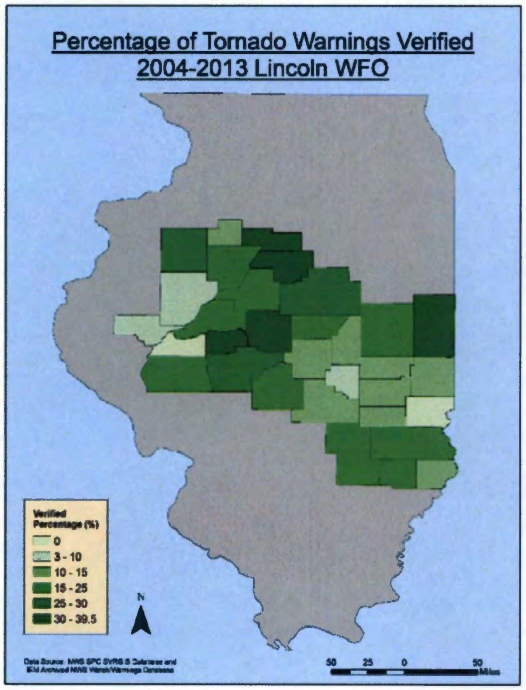


Figure 17: This map shows a county by county representation of the standard deviation of tornado warning verifications in this region.

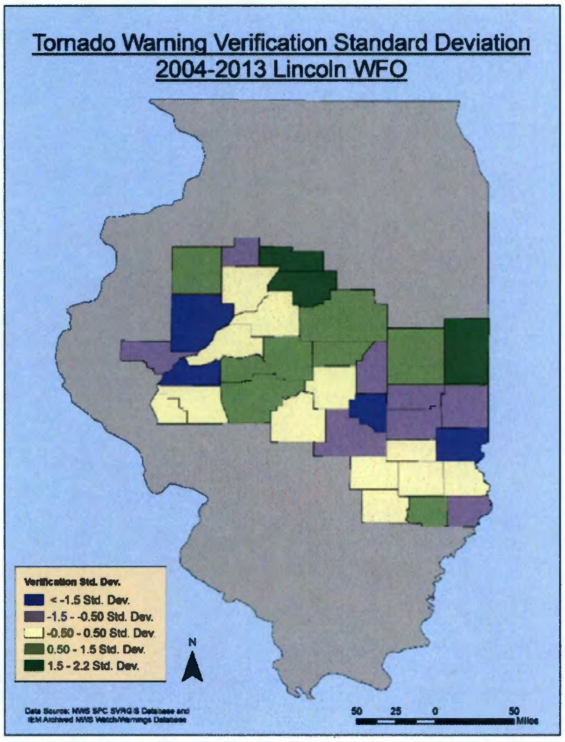


Figure 18: This chart shows the magnitudes of unwarned tornadoes in the Wilmington CWA.

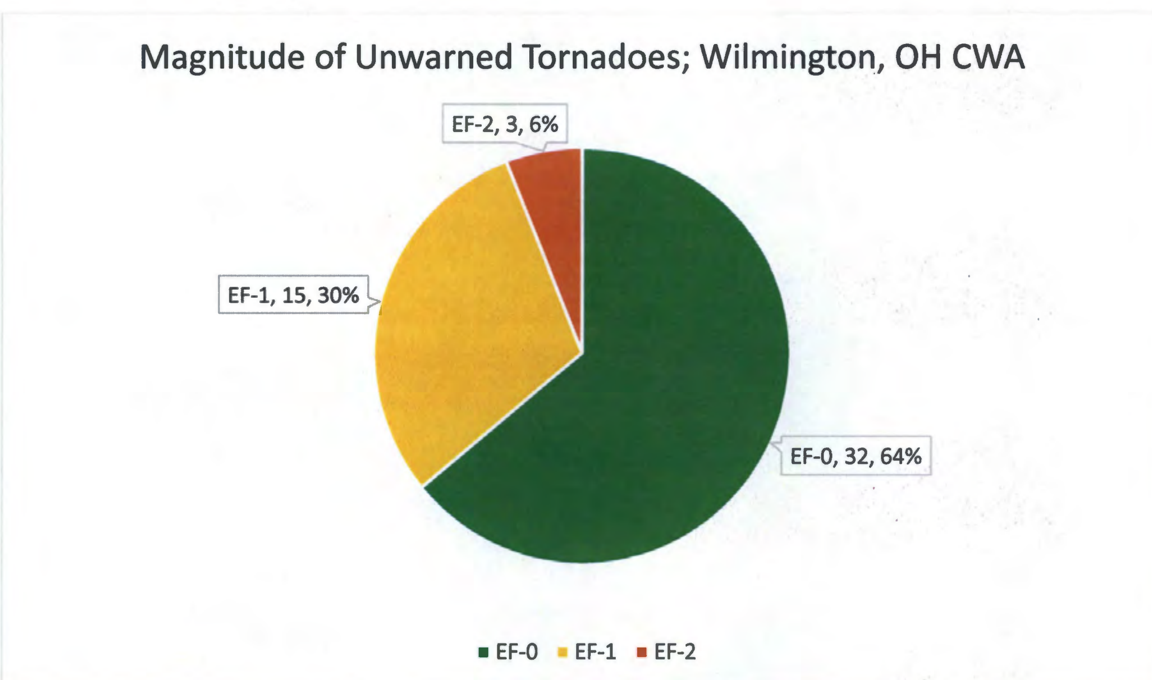


Figure 19: This chart shows the magnitudes of unwarned tornadoes in the Indianapolis CWA.

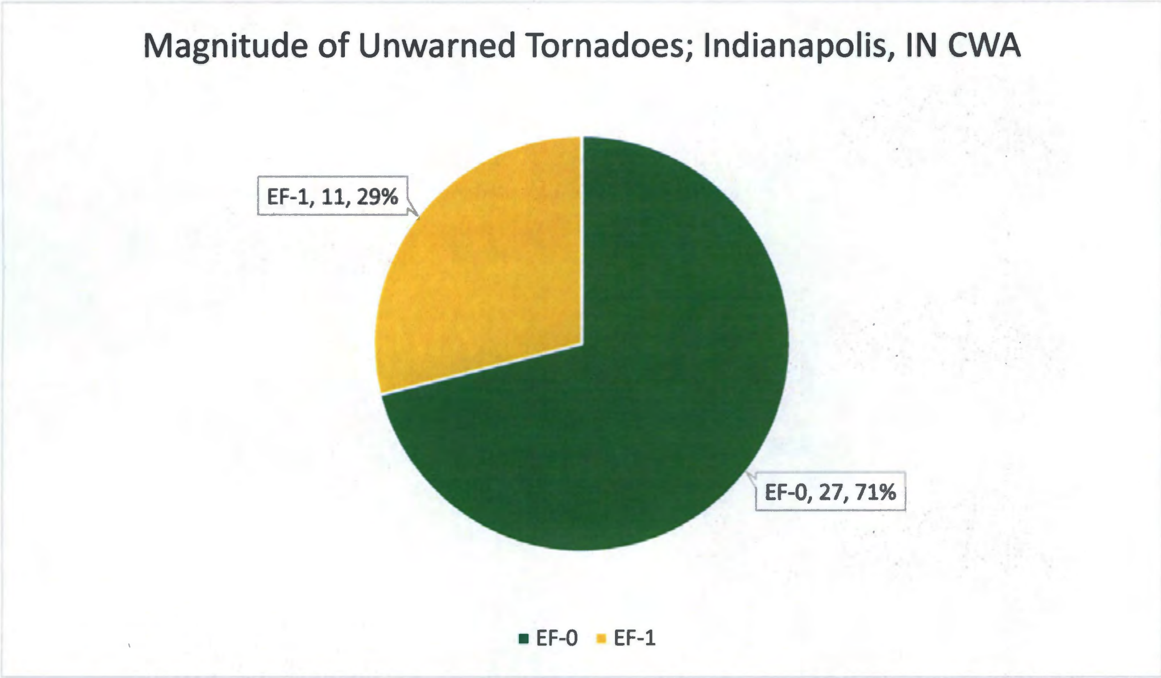


Figure 20: This chart shows the magnitudes of unwarned tornadoes in the Lincoln CWA.

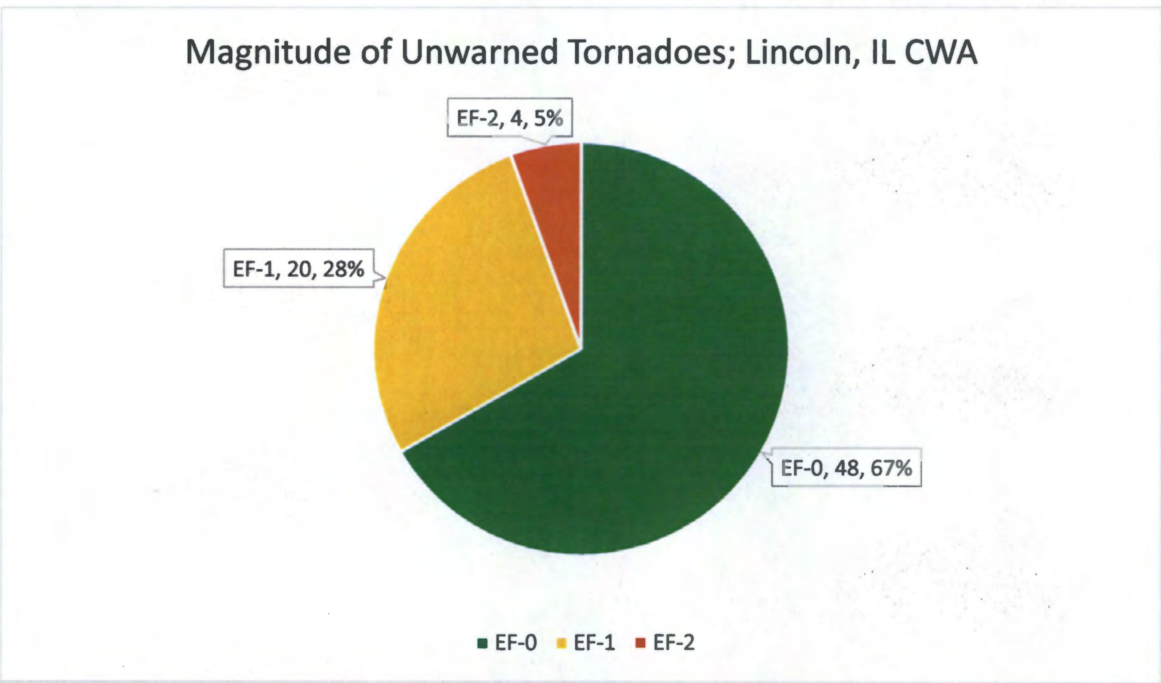


Figure 21: This graph compares total tornadoes to unwarned tornadoes in the Wilmington CWA.

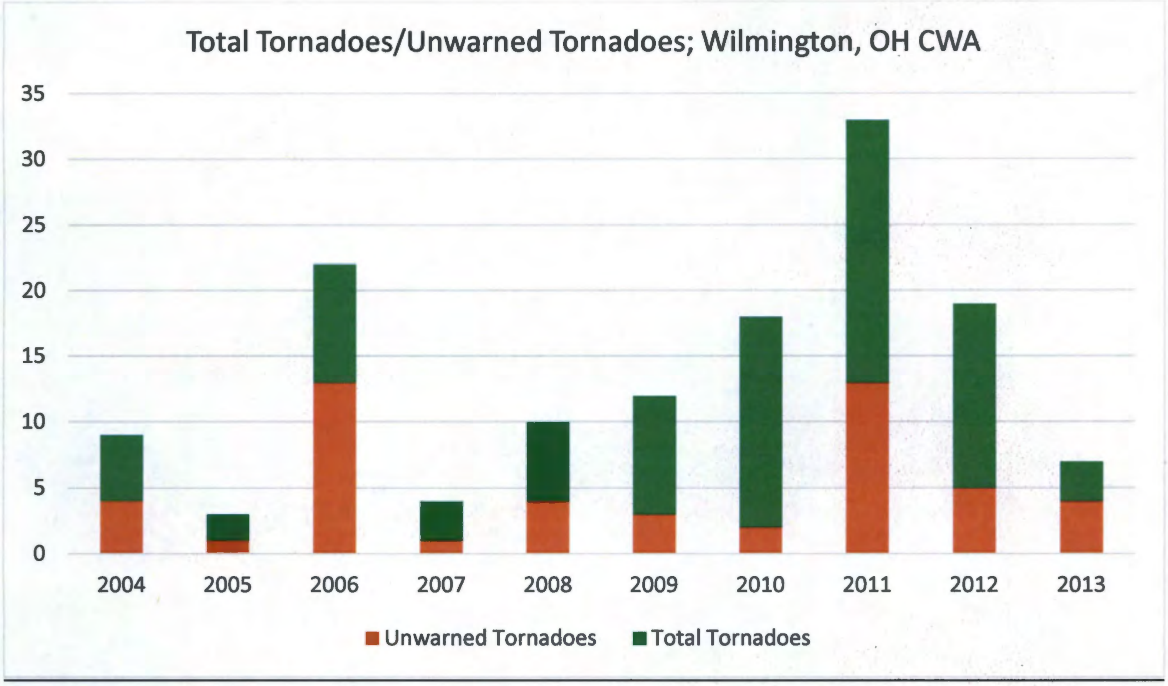


Figure 22: This graph compares total tornadoes to unwarned tornadoes in the Indianapolis CWA.

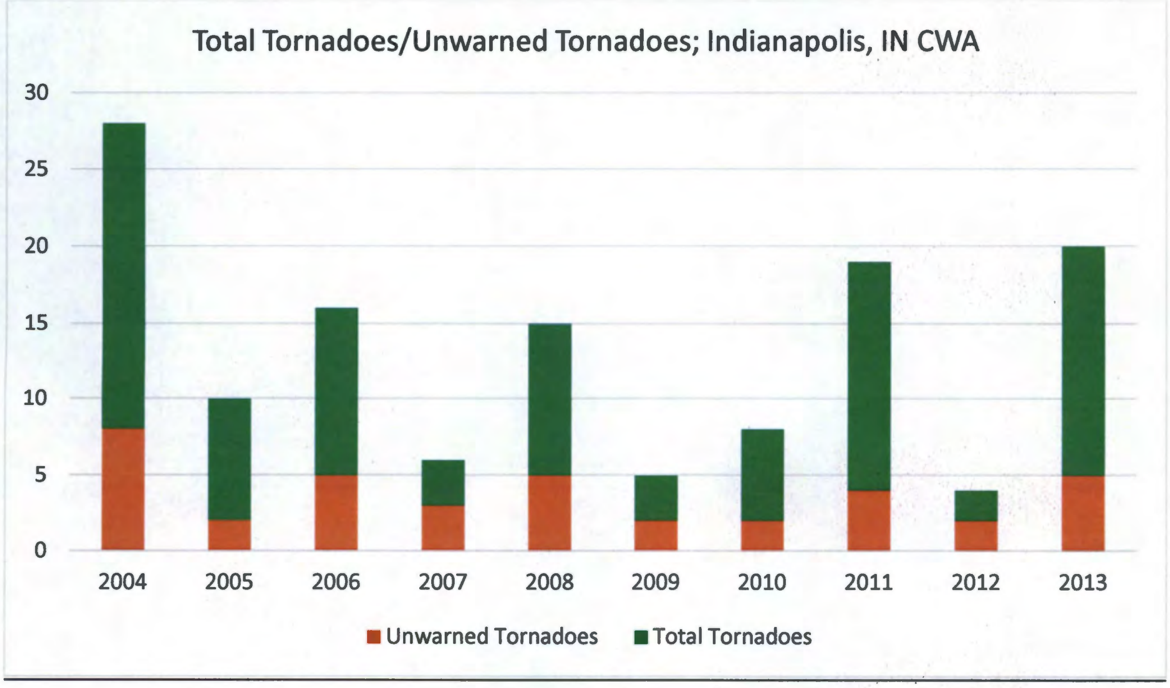
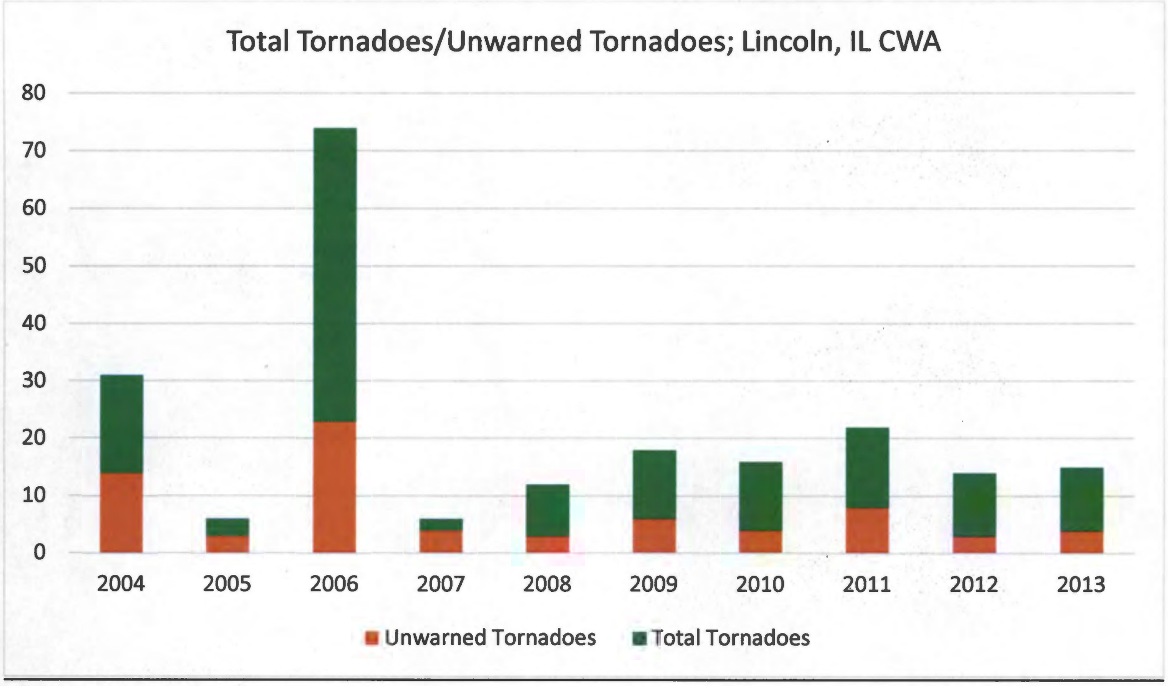


Figure 23: This graph compares total tornadoes to unwarned tornadoes in the Lincoln CWA.



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